UCRL-ID-141590

National Ignition Facility Fracture Control Plan

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May 1, 2000

U.S. Department of Energy

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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Introduction

The NIF contains a large number of optics that also act as vacuum barriers. These are subject to brittle failures that may result in significant consequences. This Fracture Control Plan identifies the requirements, needed documentation, and required actions for minimizing the potential for brittle failures of these fracture-critical components in the NIF laser system. The goal of this plan is to ensure that all fracture-critical systems present no more than a low level of risk. Risk considers both consequences (to workers, the environment, and public confidence) and probability of failure. This plan interprets and implements the guidance contained in the ME Design Safety Standard, Section 5.4, "Design Safety Standards for Fracture-Critical Components for High Power Laser Systems" (LLNL, 2000).

Summary of Design Requirements

Polished lenses and windows that are also structural elements of large vessels that transmit high fluences of laser light require special attention in design. The design should minimize the potential for component failures due to crack growth, and should also control the consequences should such a failure occur. A summary of the required design approach is given below. Detailed guidance for application of the design approach can be found in Section 5.4 of the ME Design Safety standards Manual (LLNL, 2000).

<u>Fracture-Resistant Designs.</u> The preferred approach is a fracture-resistant design (LLNL, 2000). For brittle components, the maximum possible flaw size (as limited by the size of the optic, usually taken to be the thickness of the optic) and the stress at which the component will fail from that flaw must be determined. The component can then be used at an applied stress significantly lower than the fracture stress thus determined. If this approach is followed, the critical flaw size at the actual operating stress is greater than the optic thickness and thus, unreachable. This criterion must be applied in conjunction with inspection and monitoring of crack sizes and growth.

<u>Non-Fracture-Resistant Designs.</u> Where a fracture-resistant design is inconsistent with reasonable performance (e.g., required lens thickness for fracture-resistant design is too thick to maintain laser-beam quality), an alternative approach can be applied (LLNL, 2000). In such cases, a rigorous inspection regimen must be adopted to ensure

that as any flaws grow, the components are removed before the flaws reach some fraction of the critical flaw size. Components that are non-fracture-resistant should be:

- Operated at the lowest stress consistent with the laser's performance requirements;
- Operated at a stress such that the elastic stored energy is sufficient only to cause a non-catastrophic failure, i.e., the optic will not implode, but rather will break into only two fragments, which will remain held in a well-designed optic mount.

The goal of the design requirements is to ensure that all fracture-critical systems present no more than a low level of risk. Risk is the probability of an event resulting in a certain consequence. Risk can be reduced by:

- implementing preventive features, which reduce the probability of the event;
- implementing mitigative features, which reduce the consequences of the event.

The fracture-resistant design described above is preventative. Failure is prevented by operating at a stress significantly below that which would cause failure for the maximum possible flaw size. Non-fracture resistant designs incorporate the stored energy criterion as a mitigating factor. Consequences of failure are reduced, because the optic will break into only two fragments, rather than implode. There are other factors that can reduce the risk of an optic failure, either by preventing the failure or by mitigating the consequences of failure. These are summarized in the table below.

Table 1: Preventive and Mitigative Features for Optics

Preventive Features	**Mitigative Features**
fracture-resistant design	stored energy criterion
rigorous inspection/replacement program	small area optic
low laser fluence	small vacuum volume
clean optic	rupture vent panels
low stress mounting	stay-out zones
safety note, review	secondary containment system

Application to NIF

Where possible, NIF optics should be designed to be fracture-resistant. Where this is not practical due to cost or performance constraints, the optic should be designed to meet the "non-fracture-resistant" design criterion related to stored energy. Preventive and/or mitigative features should be added to the design until the optic presents a low level of risk, based on safety and health, environment, and political impacts. The risk can be further reduced based on cost, schedule/downtime, or other programmatic impacts.

All vacuum-loaded optics on NIF require an Engineering Safety note. The graded approach should be applied to safety note preparation. For example, if a small optic is used as a vacuum barrier on a small vacuum volume, then the safety note can be simple and short.

NIF optics must be periodically inspected, and damaged/flawed optics must be removed before the crack size reaches a level of concern. Details on the required inspection program are summarized later in this plan.

All NIF fracture-critical systems shall present no more than a low level of risk. The process for assuring this begins by assessing the risk level of the optic without preventive or mitigative features. If the risk is low, no risk reducing features need be considered in the design. If the risk is medium or high, appropriate preventive or mitigative features for the system must be identified. The risk should then be reassessed, with the preventative or mitigative features accounted for. This process should continue (i.e., consider additional preventive or mitigative features and reassess the risk) until the risk is determined to be low. In addition, if the consequences of failure, without mitigating features, would be low, medium or high, an appropriate inspection program must also be established. If the consequences of failure would be negligible, a formal inspection program is not required.

This process is summarized in the flow chart in Figure 1. The methodology used for assigning risk to optics is given later.

An Engineering Safety Note is required for all vacuum-loaded optics in the NIF. A current list of NIF vacuum-loaded optics is given in Table 2. Safety notes will be prepared in accordance with the Mechanical Engineering Design Safety Standards, Chapter D, Mechanical Engineering Safety Notes (LLNL, 1995).

Consideration should be given to each of the following elements in each Engineering Safety Note:

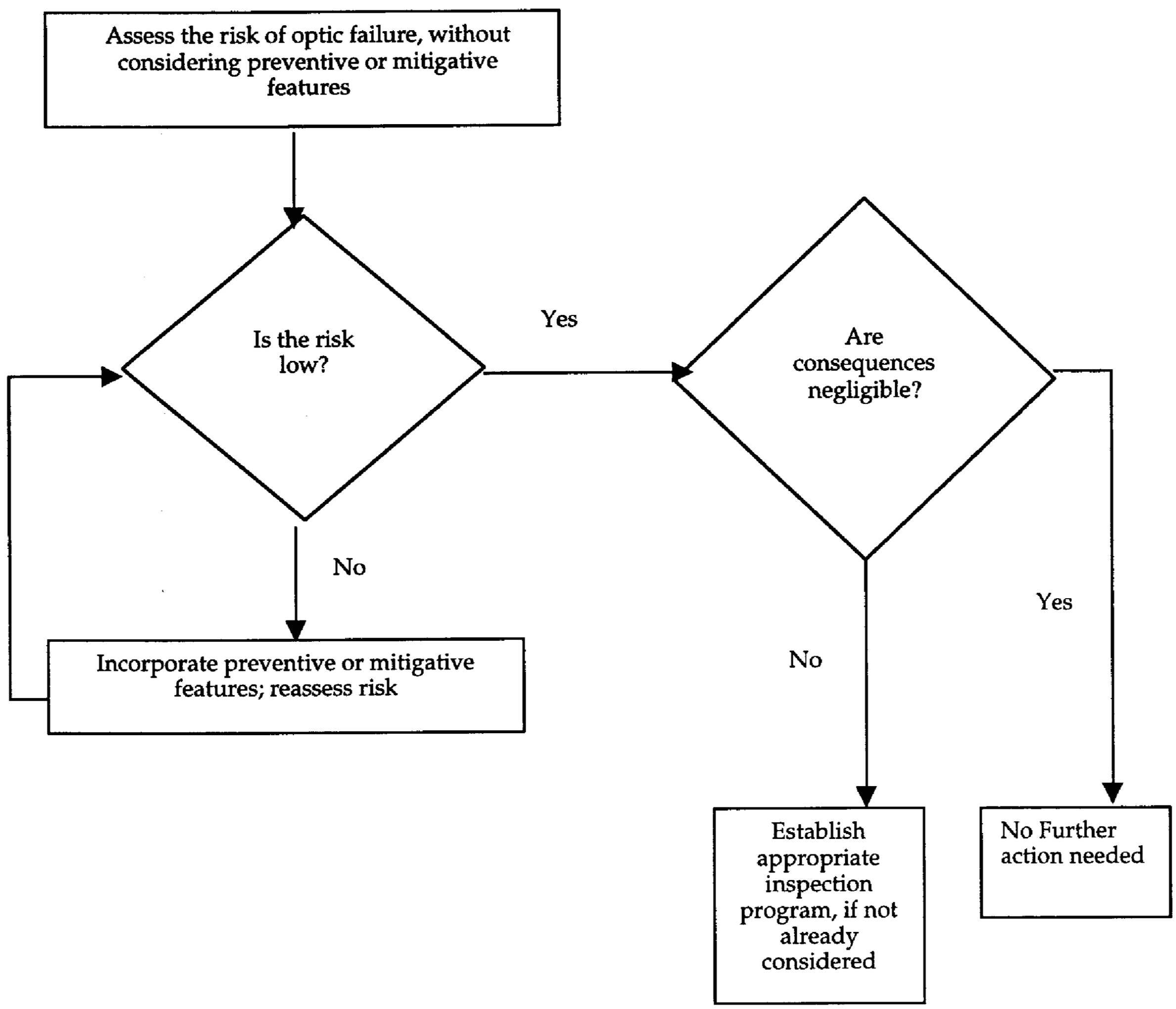

Figure 1. Process for Assuring Low Risk Vacuum-Loaded Optics Analysis and Documentation Requirements

Table 2. Initial List of NIF Vacuum-Loaded Optics

Target Chamber
- Integrated Optics Module vacuum windows
- Chamber Center Reference System windows
- Target Positioner vacuum windows
- Target Alignment System vacuum windows
- Diagnostic Manipulator windows
- 3w power diagnostic signal exit window

Target Plane Diagnostic Vessel
- Integrated Optics Module vacuum window
- Prime Focus and Damage test windows
- Target Plane Diagnostic windows

Transport Spatial Filter Vessels
- Spatial filter lenses
- Relay optics 1ω windows
- Laser alignment windows
- Injection windows
- Spatial filter positioning windows

Cavity Spatial Filter Vessels
- Spatial filter lenses
- Spatial filter positioning windows

Pockels Cells
- Pockels cell windows

Multi-pass Amplifier
- Vacuum relay windows

Input Sensor
- Vacuum relay windows

Preamplifier Beam Transport System
- Vacuum relay windows

Laser Optics Damage Inspection System
- Vacuum relay windows

Target Plane Diagnostic Tables
- Vacuum relay windows

1ω Diagnostic
Vacuum relay windows

A: Description of the optic and how it will be used;

B: Operational hazards, including identification of failure modes, and identification of factors that might contribute to the fracture integrity of the optical component, such as:

- Vacuum-vessel loading, combined with other loads such as gravity, earthquake, etc.
- Laser-induced optical damage, expected magnitude, and growth rate,
- Mounting stress,
- Residual stresses in windows,
- Thermal gradients,
- Impact loading,
- Changes due to temperature, history, exposure, or other effects;

C: Operational requirements to be applied or environmental controls necessary in order to control the fracture potential of a given barrier.

D: Design calculations, including, as appropriate:

- The design stress, the maximum allowed stress (after refinishing), the critical crack size, and the allowable crack size for both the design stress and maximum allowed stress;
- Evaluation of the relative importance of stress, fracture toughness, flaw size limits, the influence of internal residual stresses and/or external stresses from the mounting, and other identified factors;
- Recommendations related to specific design considerations addressing the structure's safety and reliability, including rated capacity or design-stress level, material and/or fabrication qualification, and inspections;
- Documentation of the level of risk (see the following section for discussion on assignment of risk levels);
- Design details of any secondary containment system, rupture vent panels, or other mitigating features;
- Inspection requirements, including inspection interval and flaw-size recommendations for a particular system to ensure a component's safety with respect to failure by crack growth or fracture;

E: Testing requirements or data that provide assurance that the optic will perform as intended.

F: Labeling requirements.

G: Associated Procedures.

Assessment of Risk Level

Vacuum barrier optics can result in four levels of consequence upon failure. The consequence level assigned to an optic is based on the impacts at the operating stress. Consequences of failure in three areas must be considered: health and safety, environment, and political. If the failure could result in significant cost, schedule/ downtime, or programmatic impact, these types of consequences can also be factored in. The four consequence levels are summarized as follows:

High:	serious employee hazard; violation of law; off-site hazardous release; major loss of public confidence.
Medium:	personnel injury; violation of orders; reportable occurrence; onsite hazardous release; loss of public confidence; widespread negative publicity.
Low:	minor impact to personnel; emergency team response; reportable occurrence; contained hazardous release; minor public concern; some negative publicity.
Negligible:	negligible impact to personnel; routine operations disrupted; no reportable impact; negligible public concern and negative publicity.

For a given optic, the assigned consequence category should be the one representing the highest of safety and health, environment, or political consequences.

In order to assess the risk presented by an optic, the probability of a failure must also be factored in. Three probability categories are considered:

Low:	Extremely unlikely during the operating life (achieved, by example, as a result of fracture resistant design or combination of stored energy design, high confidence in crack growth rate and high frequency of inspections);
Medium:	Unlikely that it will occur during the operating life (achieved, by example, with stored energy design, some knowledge of crack growth rate, and inspection frequency consistent with that growth rate);
High:	Likely to occur during the operating life.

To assess the risk presented by the optic, the consequence and probability of failure must be combined. This can be accomplished in a qualitative sense by using the risk matrix shown in Figure 2. Details on the development of this matrix are provided in the Appendix. To use the matrix, first identify the appropriate consequence category, based on the consequences of failure of the optic. The consequence category assigned for the optic identifies the relevant row on the matrix. Then, identify the appropriate probability category, based on the likelihood of failure of the optic. The probability category assigned for the optic identifies the relevant column on the matrix. The block on the matrix where the consequence row and probability column intersect represents the risk associated with the optic. The shading of that block indicates the risk level. The goal is to result in a final risk level of low for the optic (any block on the matrix shown in light gray represents low risk).

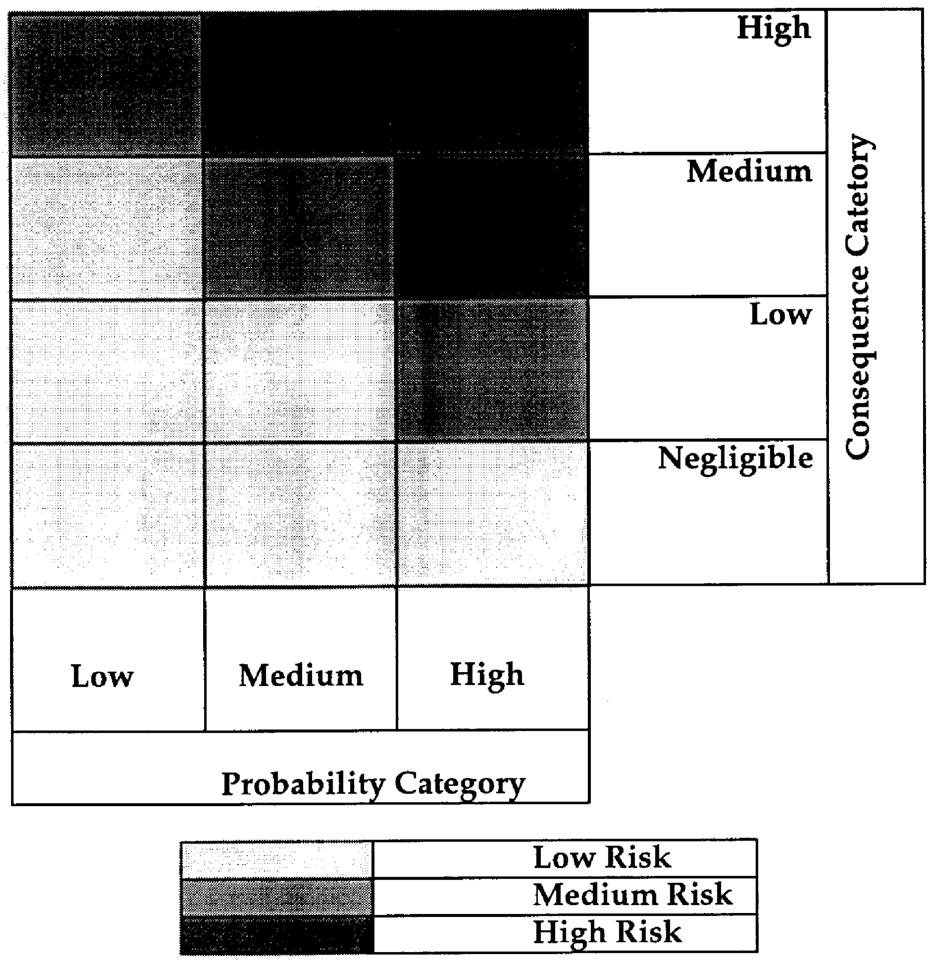

Figure 2. Risk Matrix for assessing risk associated with NIF Optics

The process described earlier (and depicted in Figure 1) requires that the risk presented by the optic be considered first without any special mitigating or preventive features or controls. For example, consider a large optic to be placed on a large vacuum vessel. If it were known that the failure of this optic could cause serious injury to a person nearby, then the appropriate consequence category to assign this optic would be "high".[1] If it were known that a failure of this type would probably occur during the life of the facility, then the appropriate probability category to assign this optic would be "high". Using the risk matrix, the initial risk associated with this optic would be "high".

Because a low level of risk is required, preventive and/or mitigative features must be factored into the design. Assume that it is not possible to develop a fracture-resistant design because this would degrade the optic's performance. The stored energy criterion could be employed, and this would reduce the consequences of failure to the "low" category. Considering this alone would reduce the risk from the optic failure to "medium". However, because an inspection program would also be needed (because the consequence of failure is low or greater), the risk can be further reduced. If it were known that the inspection program would reduce the failure probability from high to medium, then the risk presented by this optic would be reduced to low. No further risk reduction measures would be necessary.

Inspection Requirements

Inspection requirements are based on the potential consequences of failure of the optic. Regardless of the risk level assessed for the optic, if the consequences of failure, without mitigating features, would be low, medium or high, an appropriate inspection program must be established. The program must have formal requirements for inspection and definition of conditions for replacement. If the optical component would have negligible consequences upon failure, in-service inspections are not required. Credit can be given for inspection (i.e., lower probability of failure) when assessing the risk associated with an optic.

Optics should be assumed to be in a condition where they could fail (unsafe) unless the damage size is known to be below an allowable limit (safe). Determination of the damage size requires that an inspection system be available and utilized. A 'Low' consequence system (for the categories of safety and health, environment, and

[1] The political consequence may also be high. The environmental consequence is probably low, so the appropriate consequence category to assign this optic would be high.

political) requires a 'Low' level of damage inspection to reduce the probability of a failure. The critical flaw size should be large relative to the detectable flaw size, as determined by pre-service and in-service inspections. A component must be removed when the flaw's size equals or exceeds half of the critical crack size. Inspection intervals must be set so that an existing or undetected flaw should not grow to the critical size before the next scheduled inspection. The basis for the inspection interval should be documented in the Engineering Safety Note for the optic.

For a 'Medium' or 'High' consequence system, a 'Medium' or 'High' damage inspection level is required to reduce the probability of failure. For 'Medium' and 'High' consequence level systems, a rigorous inspection regimen is required to ensure that components are removed before the flaw size reaches 25% of the critical flaw size. The inspection system must be capable of detecting a flaw size equal to or less than 10% of the critical crack size. The inspection intervals must be set so that an existing or undetected flaw cannot grow to the critical size before the next scheduled inspection. The basis for the inspection interval should be documented in the Engineering Safety Note for the optic. A written procedure documenting the inspection system resolution and the inspection intervals is required.

Inspection requirements are summarized in Table 3.

Table 3: Inspection Requirements

Consequence of Optic Failure	**Inspection Requirements**
Low	$a_{critical} > 2 \times a_{inspection}$ $a_{allowable}$ is one-half of ($a_{critical} - \Delta a$), where Δa is the crack growth anticipated between inspections
Medium or High	$a_{critical} > 10 \times a_{inspection}$ $a_{allowable}$ is one-quarter of ($a_{critical} - \Delta a$), where _a is the crack growth anticipated between inspections

References

LLNL (2000), "Design Safety Standard for Fracture-Critical Components for High power Laser Systems", in progress, 2000.

LLNL (1995), Mechanical Engineering Design Safety Standards Manual, M-012, Chapter 2, "Engineering Safety Notes", 1995.

Appendix A

Development of the Risk Matrix

This appendix provides the methodology used to develop the risk matrix used to determine the risk associated with NIF optics. The approach taken was to assign qualitative descriptors to the consequences and probability of the optic failure. The consequences and probabilities can be combined using a risk matrix to obtain an assessment of the risk presented by the optic. The development of the risk matrix is the subject of this appendix.

A 3×4 risk matrix has been utilized to assess risk, with consequences on the vertical axis and probability on the horizontal axis. In order to determine the relative risk presented by each of the 12 blocks of the risk matrix, numerical values were assigned to the probability and consequence axes. The product of the numerical values of probability and consequence gives a numerical measure of risk for each block on the risk matrix. The numerical values on the risk matrix blocks were binned into risk ranges, allowing the relative risk of each of the 12 blocks of the matrix to be known.

Each NIF optic can be placed into a block on the matrix based on its associated failure probability and consequence. The risk category of the block where the optic is placed provides the risk category for that optic.

The basis for the numerical values for probabilities and consequences used in establishing the risk matrix is given below. This is followed by the approach used for binning the blocks of the matrix into risk ranges. The risk matrix is provided at the end of this appendix.

Probability Categories

The probability categories have been assigned in an order of magnitude fashion. The least likely category (Low) includes failures that will probably not occur during the operating life of the facility, or that are extremely unlikely. This category has been assigned a numerical value of 1. The most likely category (High) would include failures that may be expected to occur during the life of the facility. A numerical value of 100 was assigned to this category. The intermediate probability category (Medium) includes failures that are unlikely to occur during the life of the facility. This category has a numerical value of 10 assigned to it. The probability categories are summarized below:

Low:	Extremely unlikely during the operating life (value = 1)
Medium:	Unlikely that it will occur during the operating life (value = 10)
High:	Likely to occur during the operating life (value = 100).

Consequence Categories

The consequence level assigned to an optic is based on the impacts at the operating stress. It must consider the consequences of failure in three areas: health and safety, environment, political. The four consequence levels and assigned numerical values are summarized as follows:

High: serious employee hazard; violation of law; off-site hazardous release; major loss of public confidence (value = 1,000).

Medium: personnel injury; violation of orders; reportable occurrence; onsite hazardous release; loss of public confidence; widespread negative publicity (value = 100).

Low: minor impact to personnel; emergency team response; reportable occurrence; contained hazardous release; minor public concern; some negative publicity (value = 10).

Negligible: negligible impact to personnel; routine operations disrupted; no reportable impact; negligible public concern and negative publicity (value = 1).

Risk Matrix

The numerical values assigned to each consequence and probability category can be combined as a product to give risk values for each block of the risk matrix. The risk values corresponding to the probability and consequence scales established above are provided on Figure A-1.

For the purpose of categorizing risks according to their relative importance, the blocks on the matrix were grouped into three relative risk levels. The highest level (High) corresponds to a combined risk measure greater than 1,000; the second category (Medium) corresponds to a risk measure greater than 100 up to and including 1,000; the third risk category (Low) corresponds to a risk measure of 100 or less. Negligible risks are not specifically considered here, but they would be bounded by the low risk category.

These groupings of blocks on the matrix were determined assuming that a tolerable level of risk is equivalent to a low level of risk. A tolerable level of risk was assumed to be equivalent to that presented by a low consequence failure that is not likely to occur during the operating life of the facility (medium probability). The numerical value on the block of the matrix associated with an element with a Medium probability and a Low consequence is 100. Thus, the lowest relative risk level (Low) would include all blocks on the matrix with numerical values up to and including 100. Any element with a risk value less than or equal to the risk associated with a Low consequence event not likely to occur during the operating life of the facility (i.e., Medium probability) would fall into this risk range. The next highest level of relative risk, Medium, would include elements presenting 10 times greater risk than Low level risk elements. High relative risk would include elements presenting 10 times greater risk than the Medium category, and 100 times greater risk than the Low risk category. These groupings are reflected on the matrix.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Consequence Catetory				
High (1000)	1,000	10,000	100,000
Medium (100)	100	1,000	10,000
Low (10)	10	100	1,000
Negligible (1)	1	10	100
	Low (1)	Medium (10)	High (100)
	Probability Category		

	Low Risk (≤ 100)
	Medium Risk (>100, ≤1,000)
	High Risk (> 1,000)

Figure A-1. Risk Matrix Utilized to Assess Relative Risk of NIF Risk Elements

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